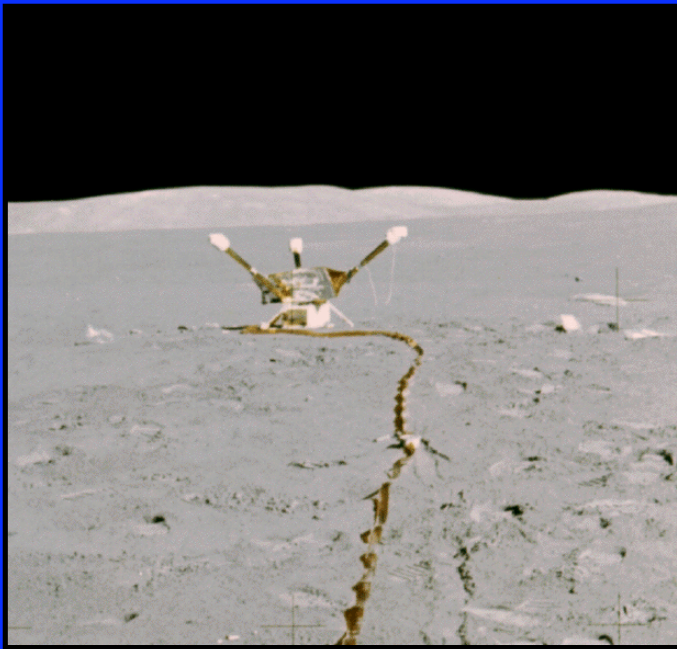


Next-Generation Electromagnetic Sounding of the Lunar Interior



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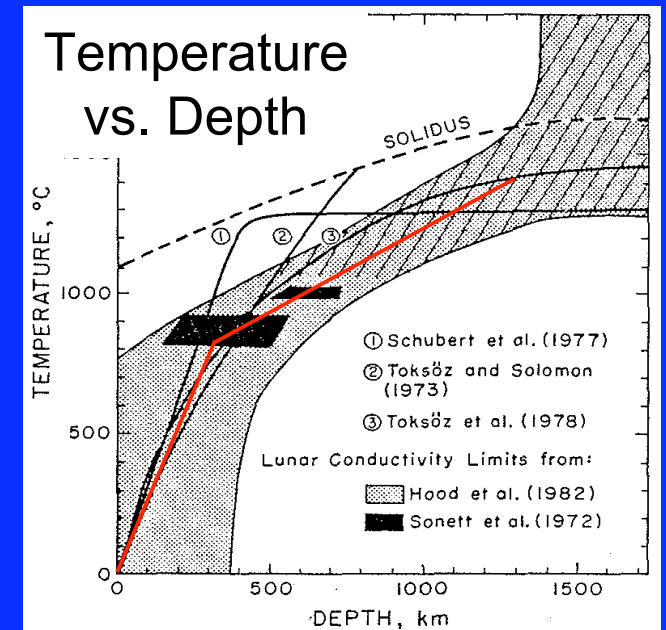
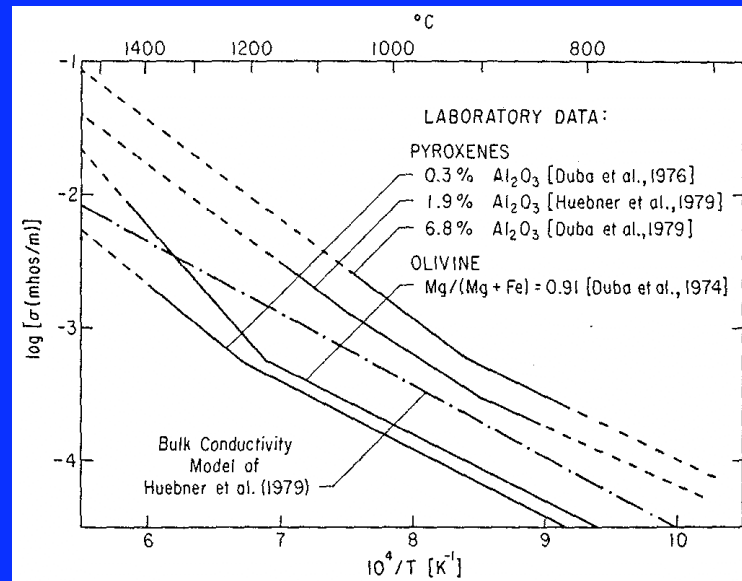
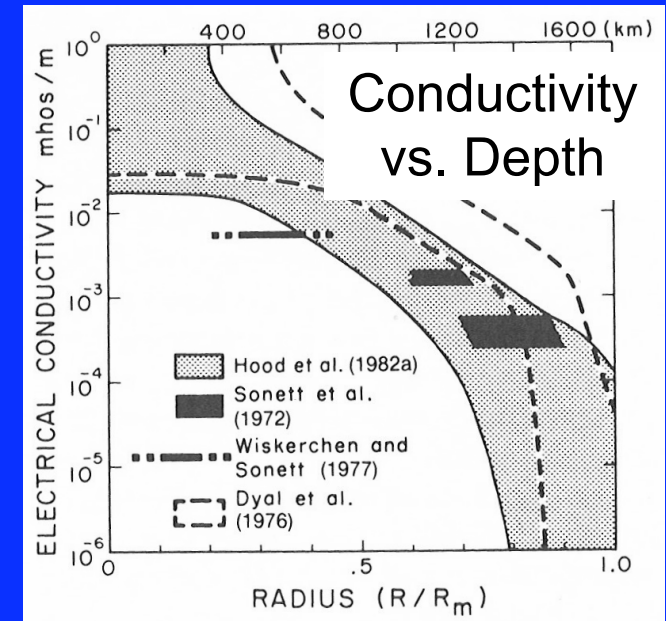
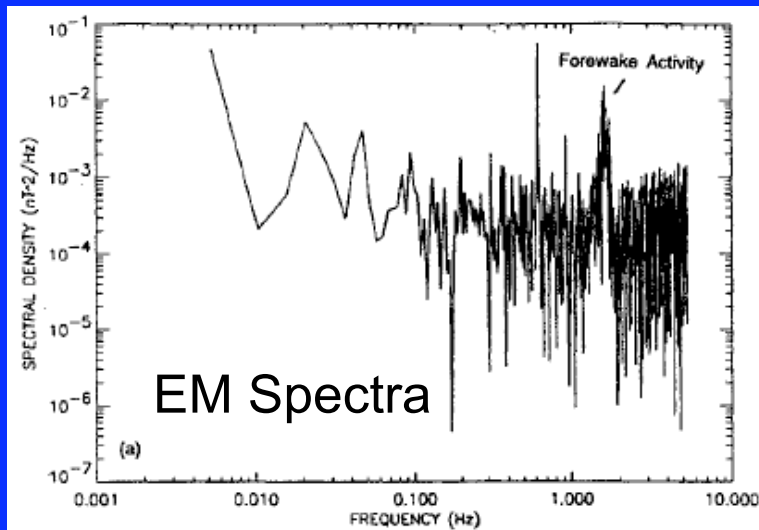
Space Sciences Laboratory

University of California, Berkeley

NASA Lunar Science Institute Meeting

July, 2008

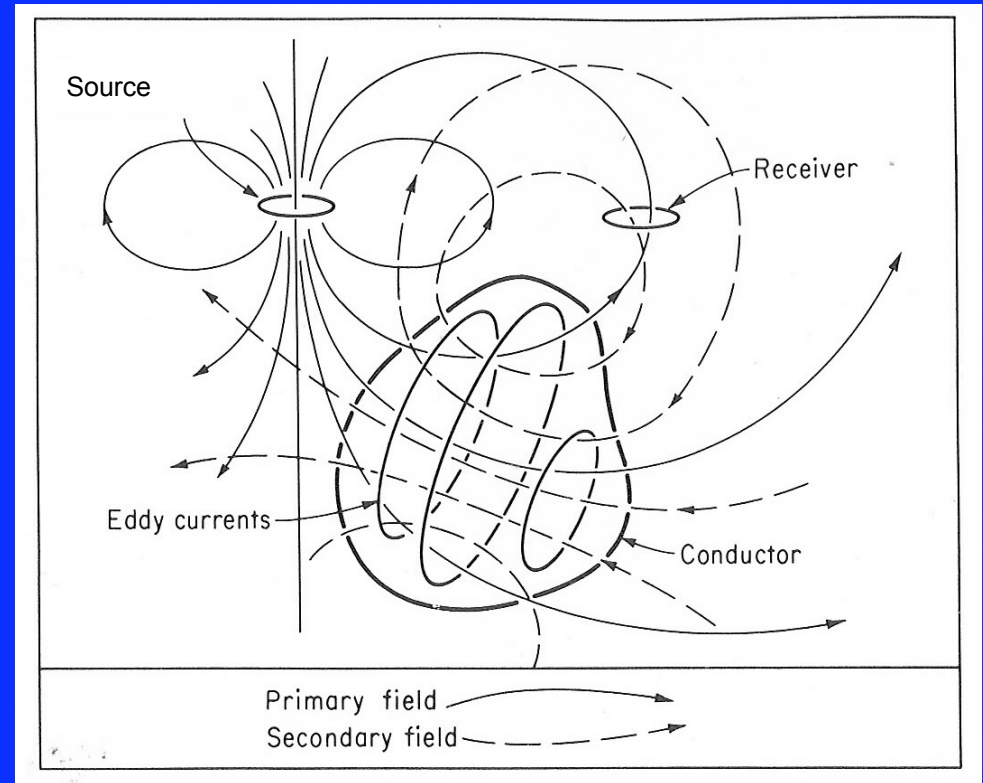
Graphical Overview



EM Sounding

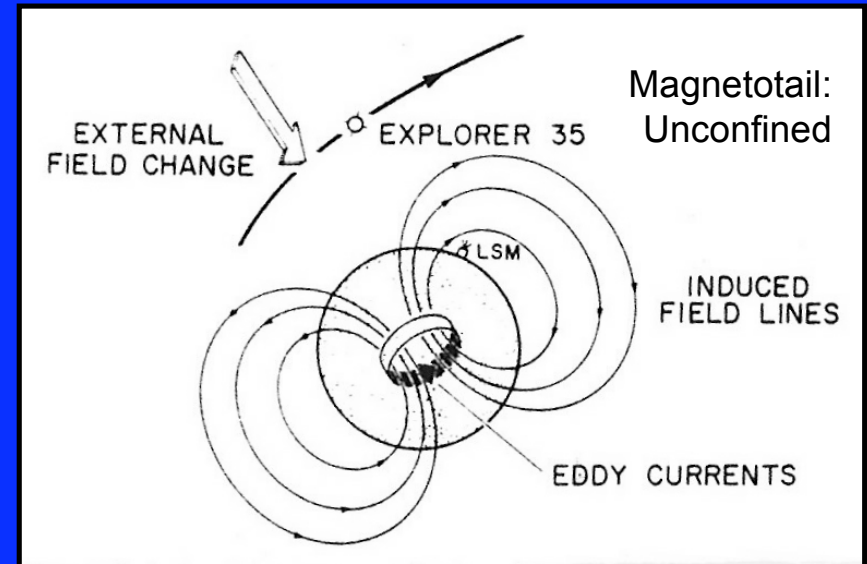
Grant and West, 1968

- Measures electrical structure from its inductive response.
 - Is distinct from propagative methods (radar).
 - Natural or artificial sources.
 - Many approaches.
 - **Skin Depth (km) = $0.5 \sqrt{\rho/f} = 0.5 \sqrt{T/\sigma}$**
f = frequency, Hz; T = period, sec
 ρ = resistivity, $\Omega\text{-m}$; σ = conductivity, S/m

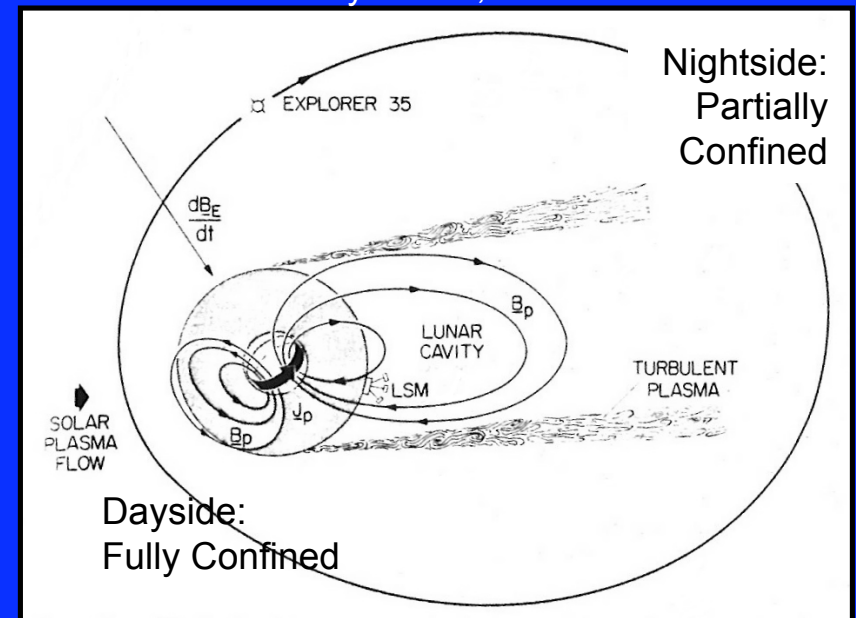


Apollo EM

- Transfer-Function Method
 - Determine inductive signal by comparing magnetic-field measurements from orbiting and surface magnetometers.
 - Whole-moon, radially-symmetric structure at lowest frequencies (dominantly 10 μ Hz–10 mHz).
- Science Results
 - Few percent free iron in the mantle; several percent total iron
 - Core radius < 400 km.
 - Best estimate (Hood 1996) using *single* instrument (Lunar Prospector) assuming perfect conductor.
 - Constrained deep mantle geotherm.
 - Shallow thermal structure consistent with heat flow.



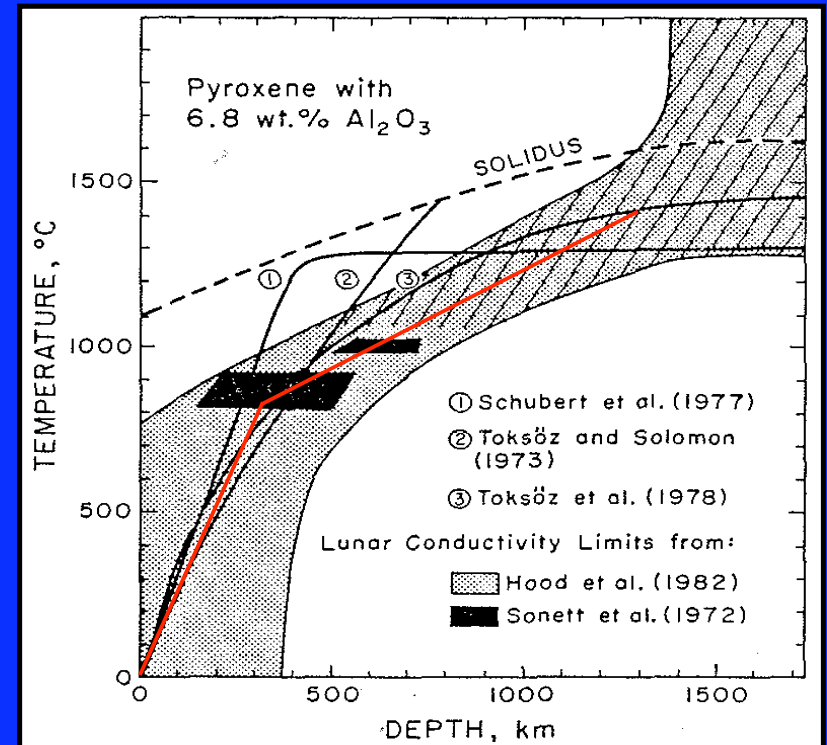
Dyal et al, 1974



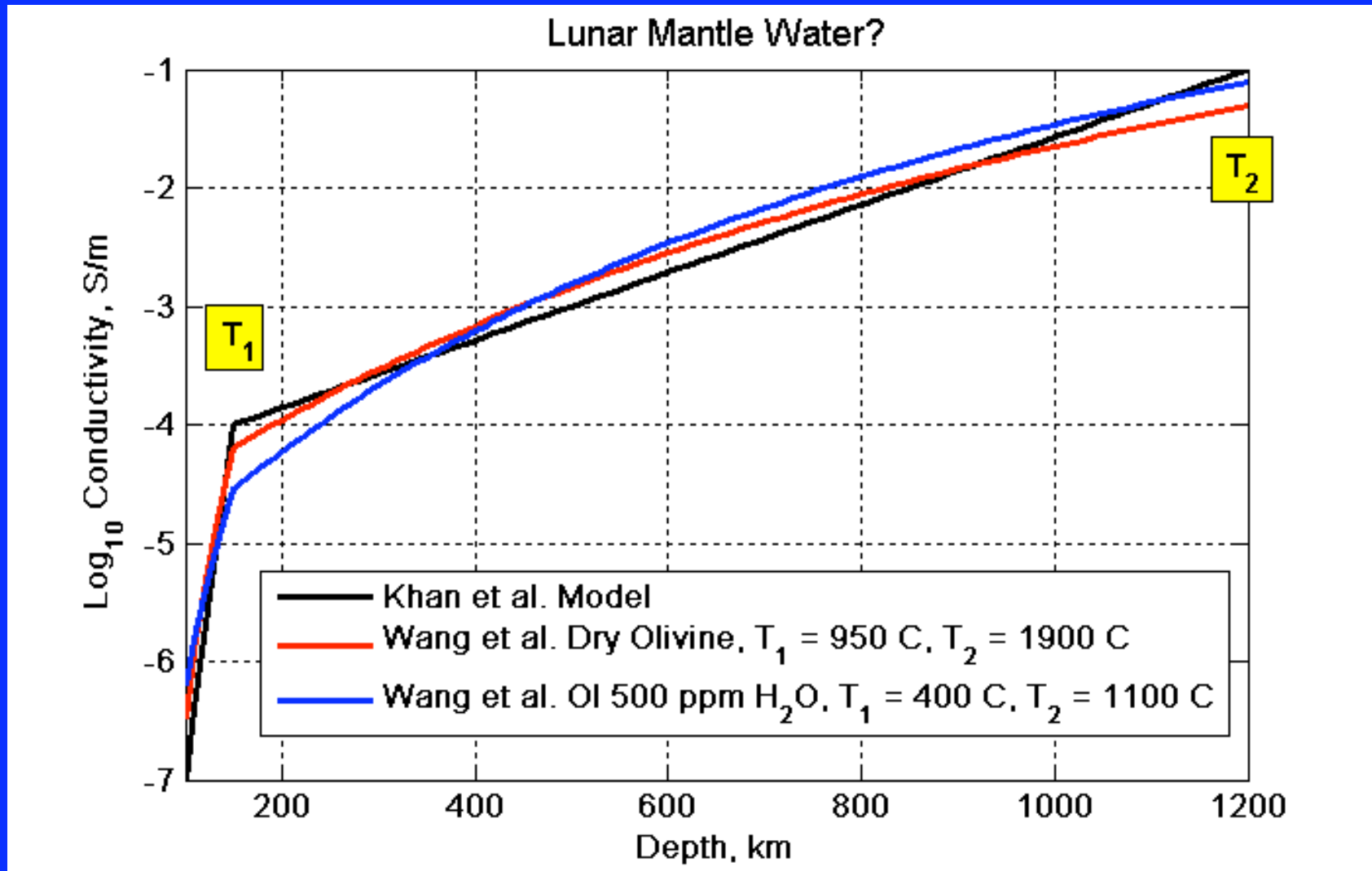
What's Next?

Sonett, 1982

- Resolve outmost several hundred kilometers
 - Lithospheric thermal gradient
 - Base of magma ocean
 - Major crustal heterogeneity (PKT / FHT / SPA)
 - Requires higher frequencies than measured by Apollo ($\gg 1$ mHz).
- Constrain composition of the mantle.
- Discriminate molten-silicate vs. solid-metal core?
 - Requires very long-period signals (days-weeks).
 - Done better with seismic network.



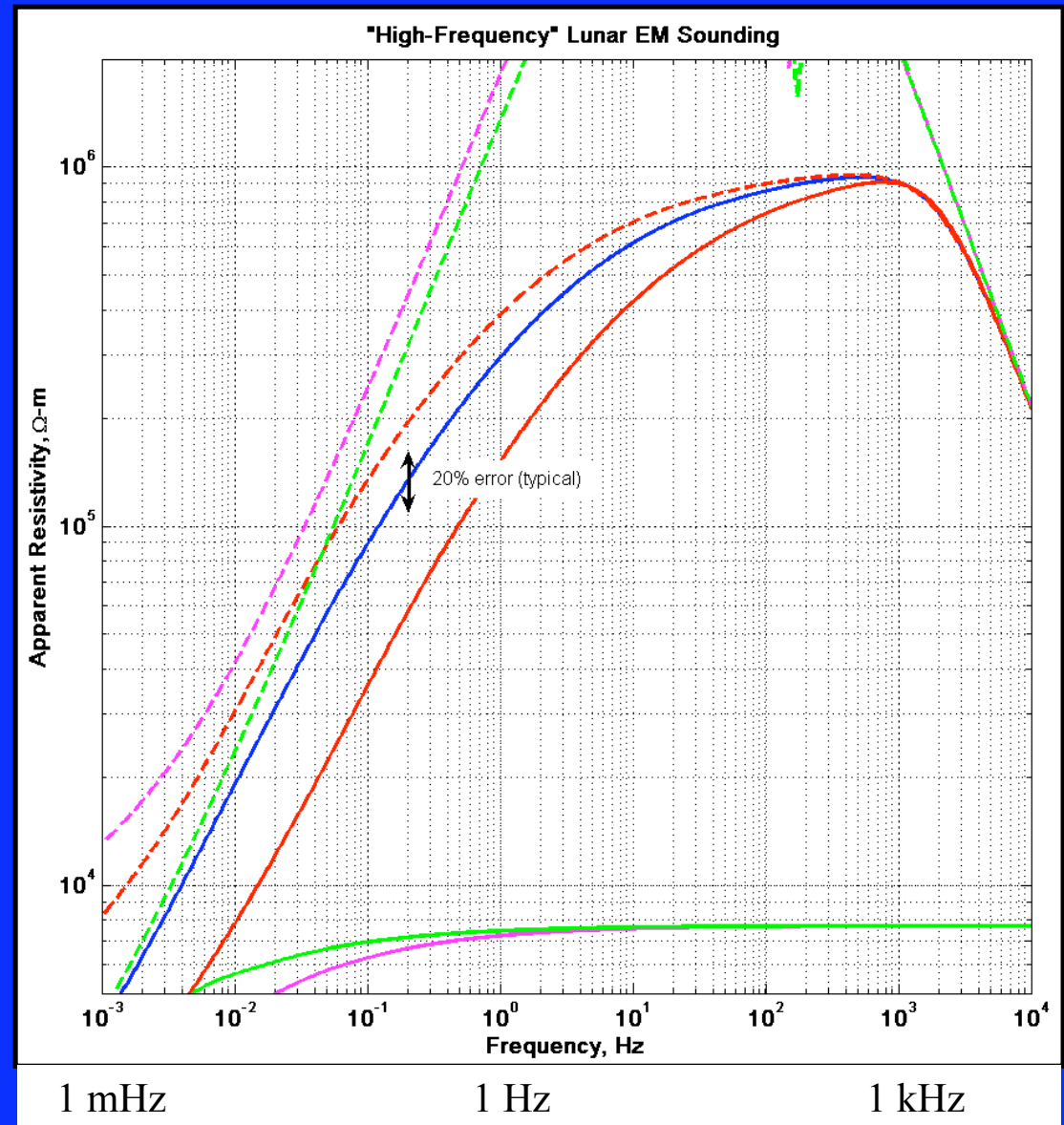
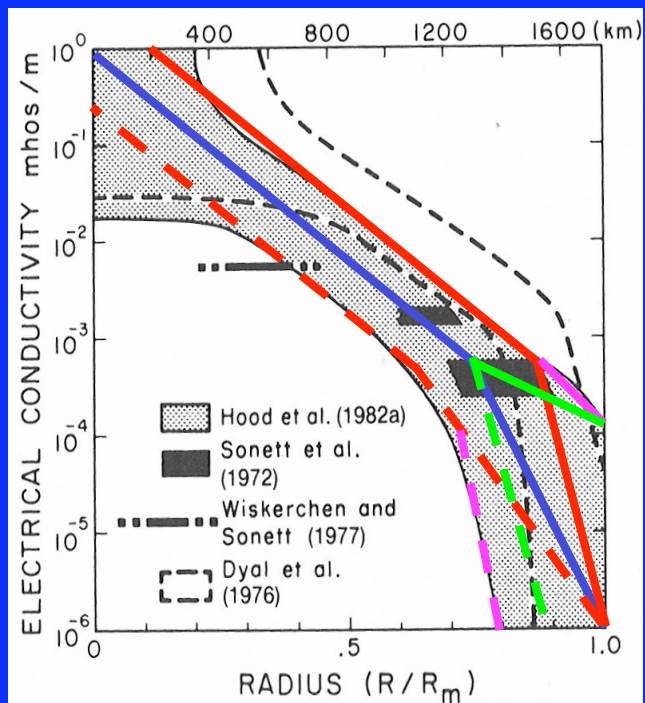
Mantle Water Content



- Few hundred ppm water can fit electrical conductivity at reasonable temperatures.

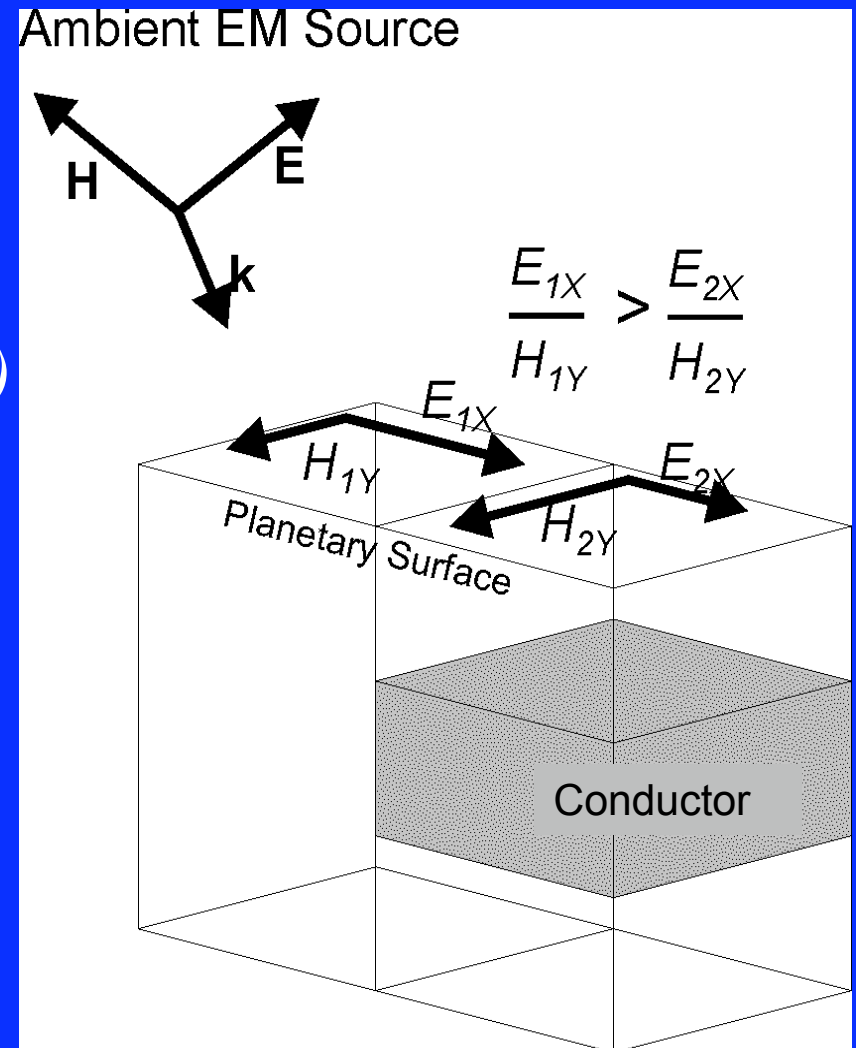
Upper-Mantle Structure

- Frequencies >10 mHz required to resolve conductivity ambiguity <500 km depth.
- Propagation >0.1 -1 kHz.
- Energy cutoff >100 Hz



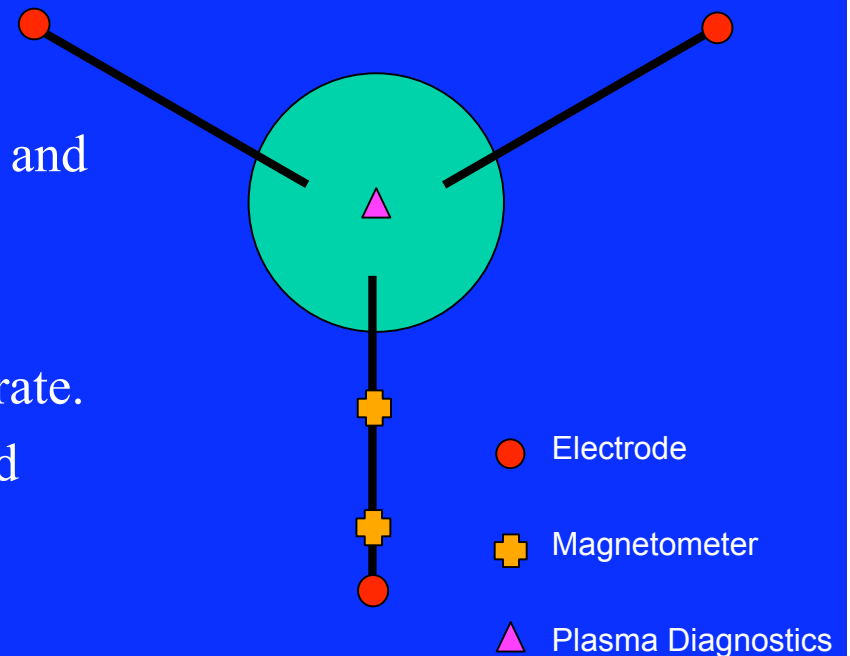
Implementation

- Wavelengths $\sim 1\text{-}10$ mHz are comparable to lunar radius.
 - Transfer-function method breaks down.
- *Magnetotelluric Method (MT)*
 - Single-station sounding using correlation of electric and magnetic fields.
 - New challenges for spaceflight application
 - Shorter baseline for E-field measurements
 - Plasma environment



Lunar Magnetotelluric Sounding

- 2x three-component fluxgate magnetometers
 - Horizontal components used in MT sounding; vertical is check and/or GDS.
 - Two magnetometers mitigate S/C interference by differencing method.
- 3x electrodes (together, the electrometer)
 - Form orthogonal horizontal electric field components from 3 voltage probes.
 - 3-4 probes away from S/C preferred.
- 1x Plasma Diagnostics package
 - Use to characterize plasma environment and thus eliminate non-inductive fields.
- Operations
 - Onboard spectral estimation to cut data rate.
 - Operate during magnetotail passages and nights to minimize plasma effects.
- Resources: Several kg, W, \$M

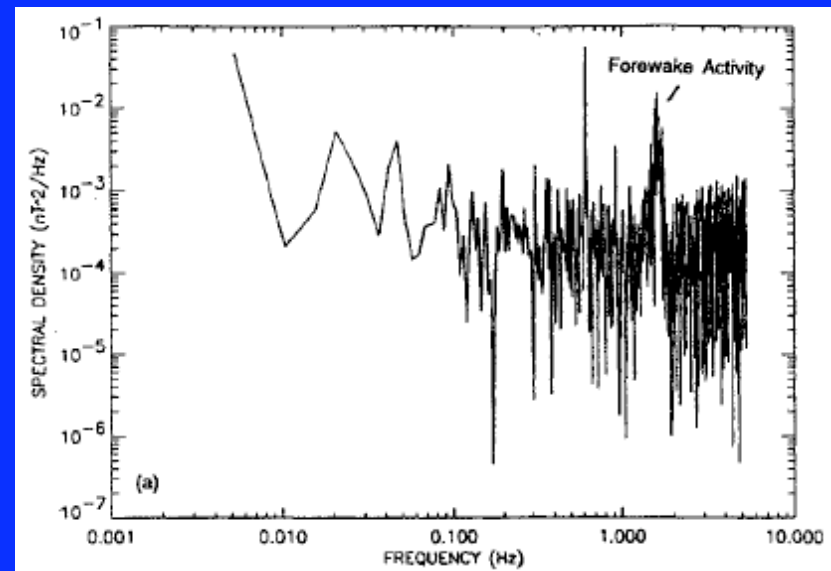
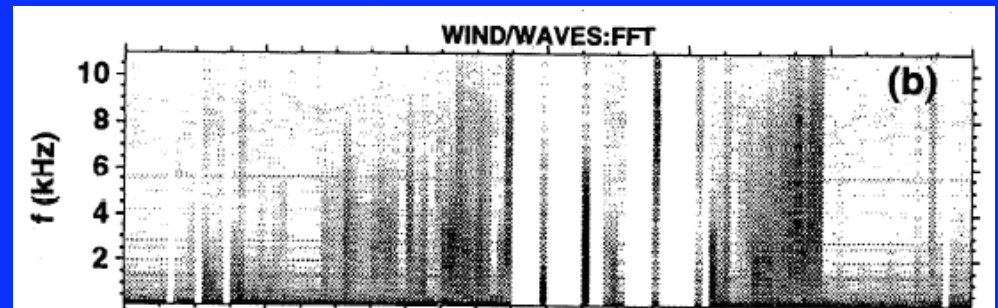
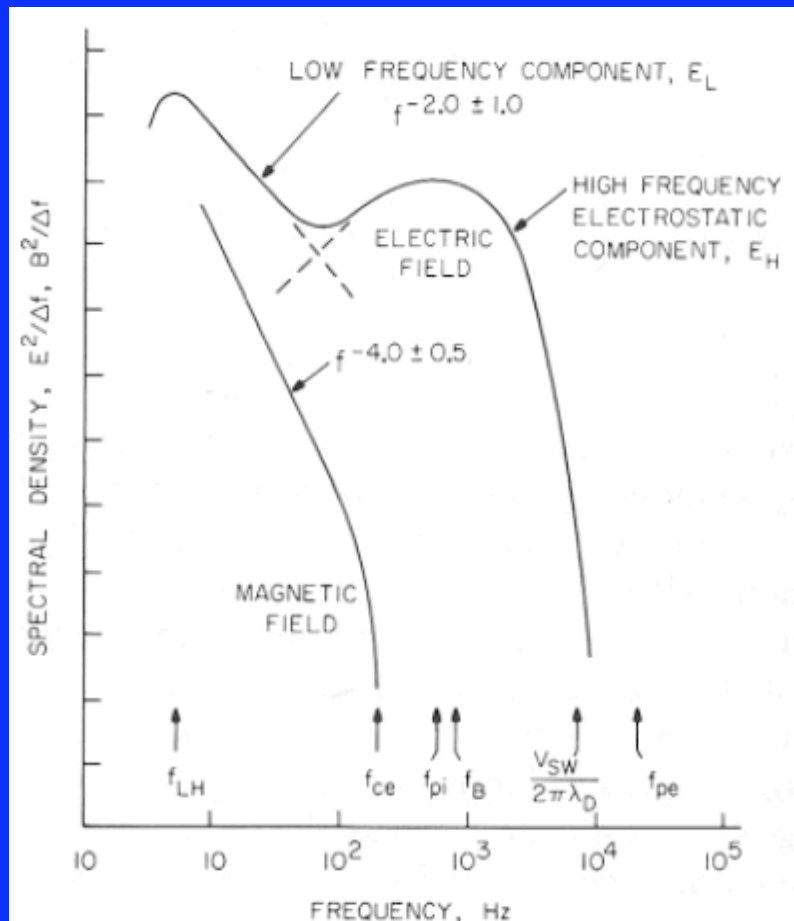


(not to scale)

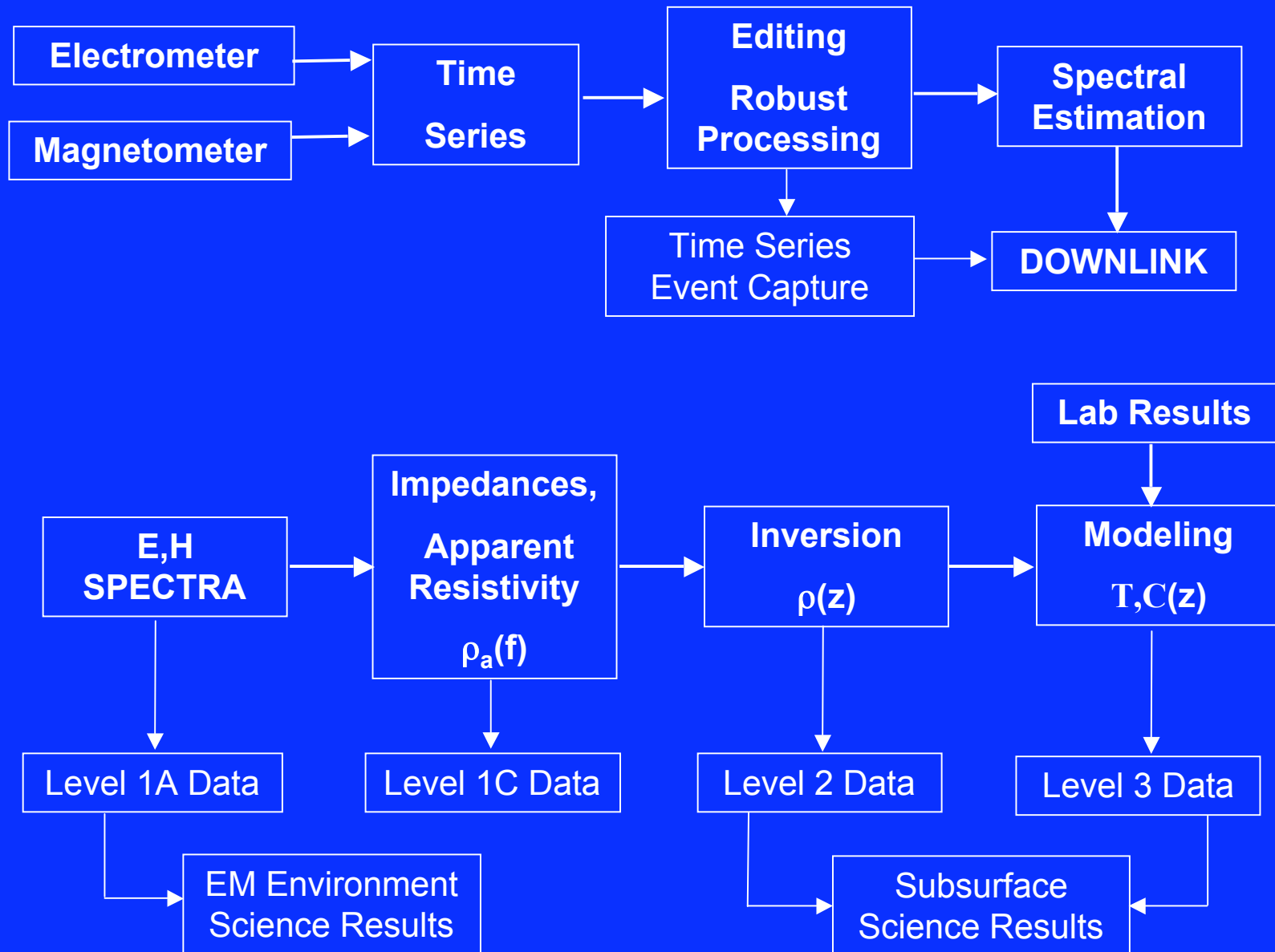
Conclusion

- EM constraints on core maximized from Apollo and Lunar Prospector.
 - *Unless* very long periods days-weeks can be accurately measured.
- Further lab/theory on electrical conductivity can elucidate linked constraints on mantle temperature vs. water content.
- Magnetotelluric sounding can measure high frequencies necessary to resolve upper 500 km, which includes former magma ocean as well as present lithospheric thickness and its lateral heterogeneity.
 - International Lunar Network

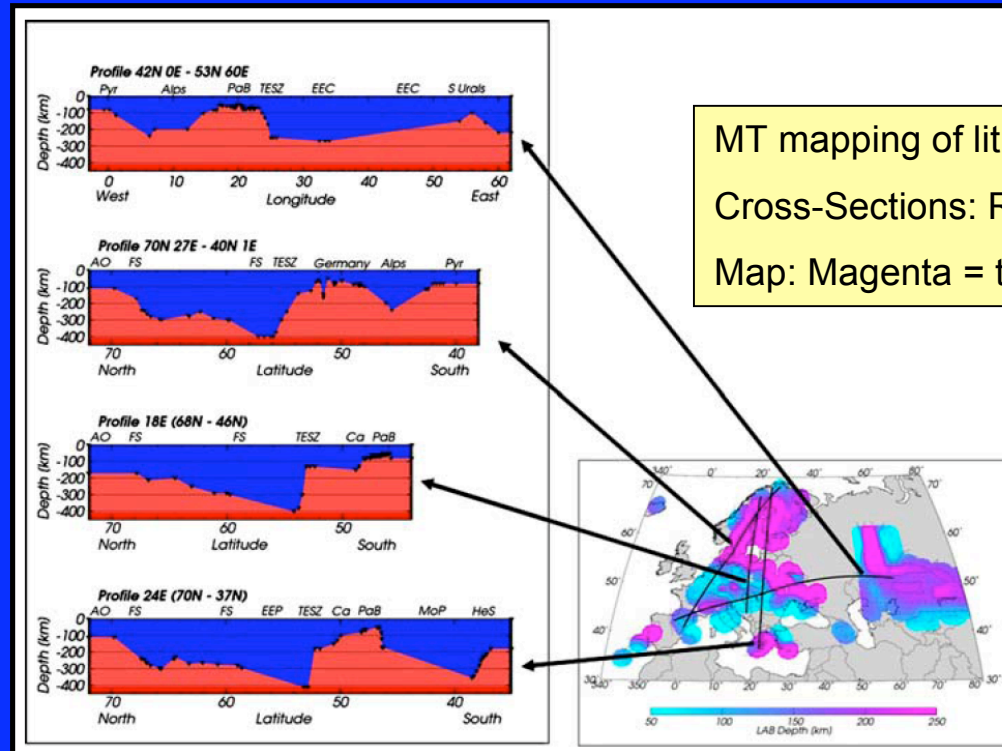
Sources



Data Flow



EM Sounding of Earth's Lithosphere

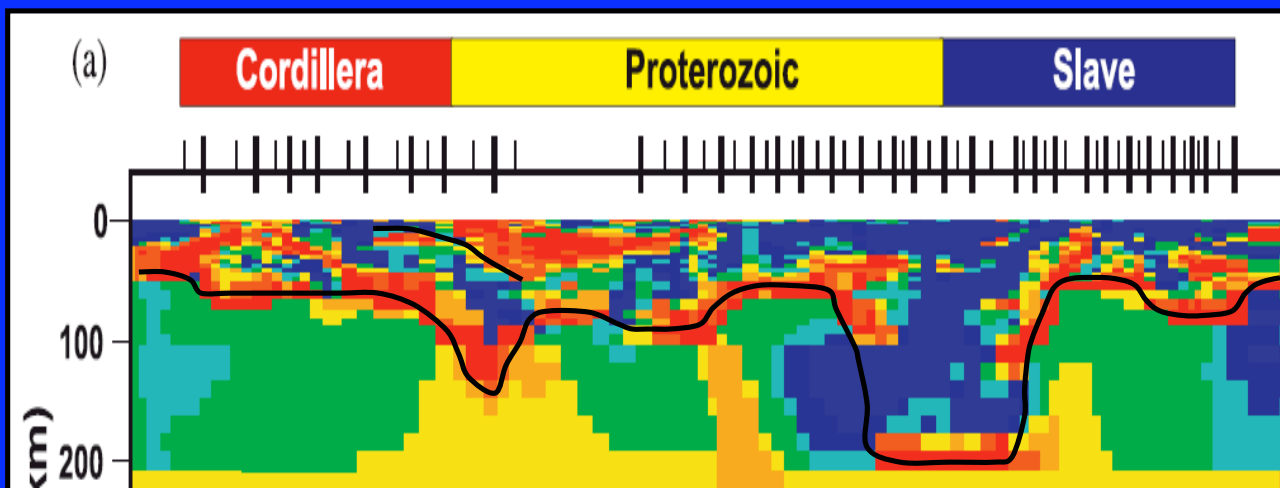


MT profile across NW Canada (Jones *et al.*, 2005).

Red = conductive
Blue = resistive.

Major conductor at 50-200 km depth (black outline) generally interpreted as top of asthenosphere.

Subducted slab (suture zone) imaged between double black lines.



Overview

- *Goal*: Understand interior structure and thermal evolution of the Moon.
 - Complements seismology and/or in situ heat flow.
- *Objective*: Infer internal temperature and composition.
- *Investigation*: Determine electrical conductivity structure of the lunar interior.
- *Measurements*: Frequency-dependent apparent conductivity (EM impedance or transfer function) using one or more of a variety of methods.
- *Auxiliary results*: Electromagnetic environment, crustal magnetism.